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The influence of different joining processes on mechanical performance of carbon fiber/polyamide (CF/PA6) composites

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ABSTRACT
Carbon fiber (CF) reinforced polyamide (PA6) composite materials are broadly used as structural materials in the automotive and aerospace industries due to their distinguished properties. However, due to requirements for the structural integrity of composite materials, there are still limitations in connection of the actual production of CF/PA6 composite. Strong joints of CF/PA6 laminates are highly required for the lightweight design in many fields. Aiming at making comparisons, different processing methods such as adhesive bonding and thermal jointing to form single lap joints between the two CF/PA6 composite laminates are studied. The influences of different processing methods and parameters on the shear strength of joints were also studied. Results showed that conventional adhesive bonding is quite easy to handle and may form rather stronger connections. Thermal joining based on electrical conductors of CF can be used to form a thermoplastic flexible joint design. Thermal joints by hot pressing can further increase the connection strength; when formed by hot pressing under optimum conditions of 250 °C and 2.5MPa, the joint has a shearing strength of 138.85 MPa. It is consequently confirmed that a strong joint of CF/PA6 composite parts could be obtained by thermal joints via the hot pressing process.

KEYWORDS: *Carbon fiber (CF), polyamide (PA6), adhesive bonding, thermal joining*

1. INTRODUCTION

Carbon fiber reinforced thermoplastic polymeric composites (CFRTPC) are increasingly being used in the automotive and aerospace industries application to produce lightweight and more fuel-efficient vehicles [1]. In this regard, polyamide (PA6) composite materials have become very attractive engineering material, mainly because of their outstanding mechanical properties, low cost, excellent chemical resistance, and ease of handling [2]. With the continuous development of composite material technology, the integrity and integration of composite material structure have become an important technique for these materials [3]. However, due to the requirements for the integrity of composite materials, there are still connection problems in the actual production of CF/PA6 composite structures [4]. Because of the joints are considered obviously the weakest link of the overall composite structure, more than half of the damage in the composite occurs at the joints [5]. The connection method of composite materials depends on the function and technical conditions of their products. The connection form and method are one of the important conditions for improving the strength of the composite structure, reducing the weight of the structure, and giving full play to the excellent properties of the composite [6]. Recently, many researchers investigated on the feasibility of different joining methods on the reinforced thermoplastic polymers include laser joining, thermal joining, riveting, and adhesive bonding [7-9]. *Gonçalves et al*. investigated on the feasibility of friction spot joining on (CF/PA66) laminate through optical microscopy and lap shear testing [10]. *Gao et al*. performed the ultrasonic joining of 4-mm-thickness of CF/PA66 composites in lap configuration and validated the weldability [11]. Among them, the adhesive joining techniques are broadly used to join the composite laminates through paste the adhesive. The advantages of adhesive connection are high connection efficiency, enables good stress distribution, suitable for connecting special-shaped and complex parts, corrosion resistance, good fatigue resistance, simple process, easy operation, energy-saving, and certain economic benefits [12, 13]. However, adhesive bonding shows some drawbacks and special requirements, including long processing time (due to preparation of substrate and curing time), some toxic adhesives, hazardous and environmental polluting, and difficulty maintaining uniformity in quality due to surface treatments [15]. Moreover, the quality and the bonding performance are affected by the environment (humidity, heat, and corrosive medium) [16]. The experiments and simulation analysis are pointed out that the water absorption of composite bonding adhesives largely affects the stiffness, durability, and mechanical resistance of the adhesive layer [17]. Therefore, the hygroscopicity of the adhesive and the thickness of the adhesive layer have become key factors in controlling the connection quality. Alternatively, hot melt adhesives do not require any curing step and are mainly used for faster assembly. These adhesives are thermoplastic-based, typically polyester, polyurethane, polyolefin and polyamide. Since the hot melts are applied in a melt state, their viscosity is an important parameter. These melt adhesives reach the ultimate strength upon cooling. On the other hand, hot melts have the disadvantage of limited heat resistance and strength [18].

In this study, different ways such as adhesive bonding and thermal joining to form single lap joints between two CF/PA6 composite laminates are used and their effect of joints forming for CF/PA6 composites was also studied. Optimization of the process parameters for CF/PA6 joining were relatively established. The mold temperature, mold pressure of the hot press, current and the voltage of electric heating joining were found to influence bonding at the interface.

2. MATERIALS AND METHODS

2.1. MATERIALS

CF fabrics (3K-T300-plain) were supplied by Jiangsu Yixing Carbon Fiber Fabric Weaving Co., Ltd. PA6 (film grade) was received from Huayi Plastic Products Shenzhen Co Ltd. Acrylic Adhesive M1-05 was supplied by Shanghai Scotbad Trading Co., Ltd. Acrylic adhesive Maxlokt6 was provided by Shanghai Lord Chemical Co., Ltd. Instant glue loctite 406 and Instant adhesive Loctite 496 were received from Henkel Loctite China Co., Ltd. Epoxy resin adhesive DP-460 3M was purchased from Company Shanghai Branch.

2.2. PREPARATION OF CF/PA6 COMPOSITES

The PA6 film was treated with ethanol to remove the oil and stains, and dried in an oven at 60 ℃ for 12 hours before the manufacturing procedure of composites was carried out. The laminates were manufactured by alternately placing plies of CF within a PA6 film (schematic diagram is shown in **Figure 1**) by hot press at 250 °C and a pressure of 2.5 MPa for 30 min. Subsequently, the laminates were gradually cooled to below the glass transition temperature (Tg) of PA6 resin, and demold, then CF/PA6 composite material was obtained, the volume fraction (Vf) of CF/PA6 is approximately 40%. This fraction is calculated by ordinary mathematical equations.

2.3. COMPOSITE JOINING PROCESSING

Excellent bonding connection design should make the bonding strength greater than the strength of the composites parts outside the connection area. Otherwise, the adhesive connection will become a weak link, causing premature failure of the connected structure. The three different methods for joining CF/PA6 composite laminates, adhesive bonding, electrical heating, and hot pressing are studied. The length, width, and thickness of the connecting spline of CF reinforced PA6 composite material are 100 mm, 20 mm, and 2 mm, respectively, and the adhesively bonded area is 25 mm and 20 mm (**Figure 1**). Different five types of adhesive are applied separately to connect two CF/PA6 composite laminates, including, Loctite 406 instant adhesive, Loctite496 instant adhesive, DP- 460 epoxy resin adhesive, M1-05 acrylic adhesive, and Maxokt6 acrylic adhesive. The samples were referred to as adhesive A, adhesive B, adhesive- AB-1, adhesive- AB-2, adhesive- AB-3, respectively. The long-tail clip was used to clamp the connection samples to ensure the straightness of samples. The adhesive- AB-1connection sample was placed in an oven at 80°C for complete curing and then taken out for testing. The carbon fiber energized heating joining method refers to laying of the carbon fiber tape on the surface of composite materials to be connected. The width of CF conductive tape is equal to the length of the connecting surface. The two ends of CF tape are extended to clamp the two poles of the power supply for energization. Moreover, the heating and joining of the CF conductive tape are controlled by adjusting the input voltage and input current of the two poles. The hot press equipment was used to join the two composite parts together by means of the applied pressure and temperature through a period of time. A series of samples are prepared by adjusting molding pressure and molding temperature.

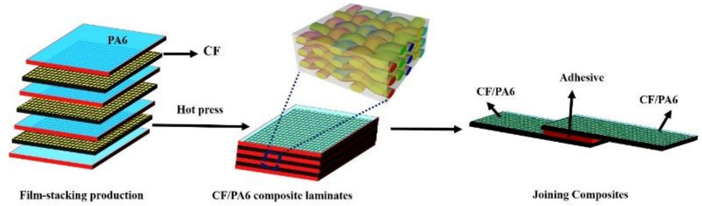

Figure 1. Composite materials fabrication and the joining process of CF/PA6 composites.

3. CHARACTERIZATIONS

Universal testing machine (TA Instruments Instron 5985, USA) was used to determine the shear strength of the connected composite material. The size of the shear strength specimen is 100×20×2 mm^3, speed is 1.0 mm/min and the overlapping part of the connecting spline is 25mm×20mm according to ASTM D1002.

4. RESULTS AND DISCUSSIONS

4.1. ADHESIVE BONDING OF CF/PA6 COMPOSITE

The influence of different bonding processes on the connection performance of CF/PA6 composites was studied. **Figure 2** shows the connection and fracture diagrams of samples connected by three different types of glue and two different instant adhesives. Referring to **Figure 2 A and B** the joints connected by Loctite 406 and Locitete 496 instant glue demonstrated adhesive failure mode and the surface of the spline was smoothly peeled off, indicating the weak adhesion between the adhesive and CF/PA6 composite laminates. As shown in **Figure 2 C**, the DP-460 epoxy resin adhesive has a relatively good connection effect, and a certain amount of glue was adhered to the surface of the spline, indicating that the connection effect between epoxy resin adhesive and CF/PA6 composite laminates was better. **Figure 2 D** and **E** showed fracture diagrams of CF/PA6 composite laminates joined by M1-05 acrylic adhesive and MAXLOKT6 acrylic adhesive. Both adhesives showed good wettability to the CF/PA6 composite laminates and a significant amount of adhesive tightly attached to the surface of the spline indicated that the join-ability was remarkably improved.

Figure 2. Fracture diagram of samples connected by different adhesives, (A) Loctite 406 instant adhesive, (B) Loctite 496 instant adhesive, (C) DP-460 epoxy resin adhesive, (D) M1-05 acrylic adhesive and (E) MAXLOKT6 acrylic adhesive.

Figure 3. Shows the shear strength of CF/PA6 jointed using five different types of adhesive. The shear strength of CF/PA6 composite laminates connected by the Locitite 406 and Locitite 496 instant adhesives was very low, showing shear strength of 17.2 MPa and 26.3 MPa, respectively. From these results, it was clearly found that these types of instant adhesive are not suitable for the connection process of CF/PA6 composites laminates. In comparison with the effect of instant adhesive, DP-460 epoxy resin adhesive has a higher shear strength (53.1 MPa). The maximum shear strength was achieved when the CF/PA6 composite laminates connected via MAXLOKT6 acrylic adhesive, suggesting that the interfacial adhesion significantly improved. Based on the shear strength analyses, it was concluded that the MAXLOKT6 acrylic adhesive can basically meet the connection requirements of CF/PA6 composite materials.

4.2. ENERGIZED HEATING JOINING OF CF/PA6 COMPOSITE

Due to the structural properties of CF, the conductivity of CF is directional and the volume resistivity of CF is about 1200×10^{-6}~$300\times10^{-6}\Omega$cm. Therefore, the morphology and distribution of CF in composite materials determine the material performance, thus the resistivity of the CF reinforced thermoplastic resin matrix composite material can be adjusted in a larger range. Carbon fiber electrodes have a wide range of applications as an electric field sensor due to the good electrical conductivity, stable performance, small size, light weight, high specific surface area, and excellent mechanical properties. Due to excellent mechanical properties of the CF, the stress concentration of the structural parts at the joints is reduced, thus the mechanical strength of structural parts can be greatly improved. A series of CF/PA6 composite joining was prepared by adjusting the current and voltage under pressure on both parts to get good consolidation and the connection process is presented in **Figure 4**.

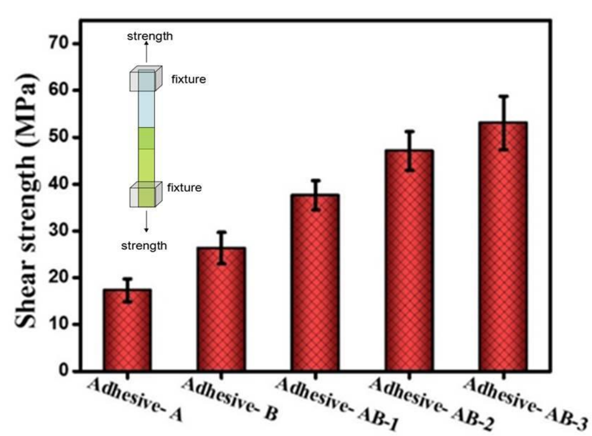

Figure 3. The influence of different bonding processes on the shear strength of CF/PA6 composites. Inset shows schematic diagram of shear strength test of CF/PA6 composite joining.

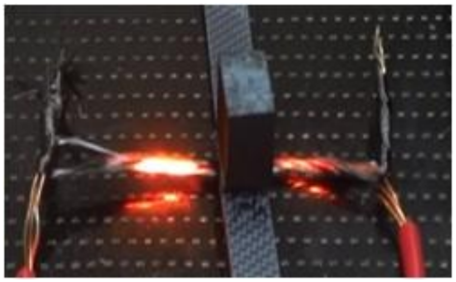

Figure 4. Diagram of carbon fiber electric heating joining process.

Figure 5 shows the effect of different voltages on the shear strength of the CF/PA6 composite material connected under the current of 1A and 2A. As shown in **Figure 5 A,** the shear strength of CF/PA6 joined under the current of 1A slightly increased with increasing the voltage, and reached a maximum value when the voltage was 10V. After the voltage was increased from 5V to 10V, the shear strength of the connected samples increased from 25.7 MPa to 62.3 MPa, showing an increase of 141.8%; this was mainly because the CF was affected by changing the voltage conditions under certain current conditions. As the voltage increases, the self-heating of the carbon fiber increases which makes the PA6 in the CF/PA6 composite material reach the above melting point and the PA6 resin matrix impregnated with the conductive CF, thereby improving the shear strength of the connected composites.

Figure 5 B shows the effect of different voltages on the shear strength of the CF/PA6 composite joined under the treatment condition of a constant energization time and a current of 2A. The shear strength showed similar behavior as composites joined under current of 1A, the shear strength of the composites increases with the increase of the voltage. With increasing of voltage from 5V to 10V, the shear strength of the connected composites increased from 45.1MPa to 81.4 MPa respectively, showing an increase of 80.75%. When the applied current was I=2A, the PA6 and polymer was melted completely and the joining area was increased. In this case, the heat generated by the self-heating of the CF under 2A led to better combination between PA6 and the conductive CF, thereby the shear strength of the CF/PA6 composites joining under 2A was showing better improvement compare to composites joining under 1A. Therefore, CF conductive heating joining can be used as a connection method for complex structural parts. Actually, these results showed much higher level of enhancements than that reported in previously studies [10, 11].

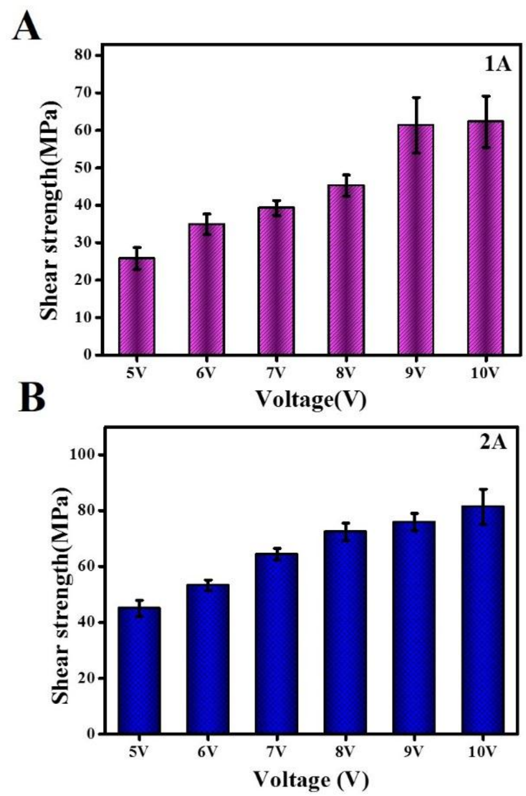

Figure 5. The effect of voltage on the shear strength of CF/PA6 composites connected samples under different current conditions

4.3. HOT PRESS JOINING OF CF/PA6 COMPOSITE

PA6 is a thermoplastic resin, so the hot press molding connection process is also an ideal connection method for connecting CF/PA6 composite laminates. **Figure 6** shows the failure diagrams of connected samples under three typical pressure conditions at 250°C. When the molding pressure was too small, the connecting spline has no obvious connection effect at the lap joint, and the surface of the spline is smooth (**Figure 6** A). When the molding pressure was too high, the connecting spline was greatly deformed at the lap joint. It can be seen from **Figure 6** C after the spline was destroyed that a large deformation has occurred inside the fiber, which is obviously not conducive to the connection effect. When the molding pressure is 2.5 MPa, the fiber was not deformed, and the failure point showed that the interaction area between the composite was large, which greatly improves the shear strength of the connecting spline.

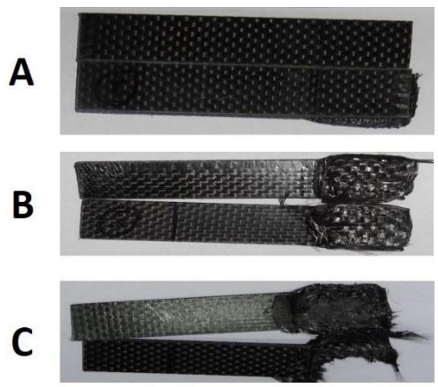

Figure 6. The influence of different pressures on the molding connection process (A) 1.0 MPa, (B) 2.5 MPa and (C) 4.0 MPa.

Figure 7 shows the influence of different molding pressures on the shear strength of CF/PA6 composite jointed under the molding conditions of 230°C. It can be seen that from **Figure 7, A** as the pressure increases, the shear strength of the connected composites initially increased and reached the maximum value at the pressure of 3 MPa with the shear strength of 84.3 MPa and then remarkably decreased. **Figure 7 B** shows the influence of different molding pressures on the shear strength of the CF/PA6 composite jointed at a molding temperature of 240°C. When the molding pressure was 2.5 MPa, the shear strength was higher than that joined under the temperature of 240°C, which about 101.1 MPa. The reason is that when the hot pressing temperature increases, the kinetic ability of PA6 molecules is dramatically increased, resulting in good connection between two composite laminates. As the molding pressure exceeded 2.5MPa, the shear strength dropped significantly. This is because of that, at a molding temperature of 240 °C and high pressure, PA6 was prone to thermal-oxidative aging, which could affect the shear strength of the connected composites. For CF/PA6 composites joined at molding temperature of 250 °C as shown in **Figure 7** C, when the molding pressure is 2.5 MPa, the shear strength reached the maximum value (138.8 MPa). When the molding pressure is 4.0 MPa, the shear strength of the joined composites was very small. This is because at high temperature the PA6 has good fluidity, thus, excessive pressure caused large deformation of the textile structure of CF in the composite material, which could seriously damage the shear performance of the joined composite material.

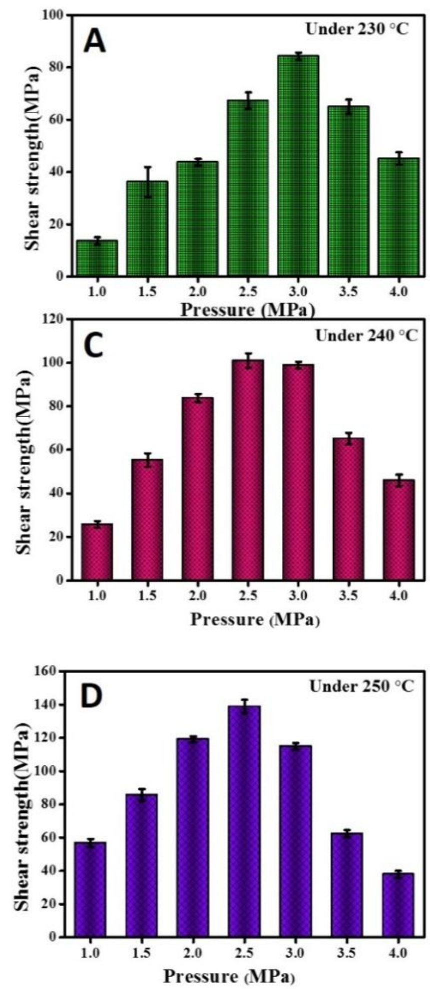

Figure 7. The influence of different molding pressures on the shear strength of CF/PA6 composite material joint samples under (A) 230 ℃, (B) 240 ℃ and (C) 250 ℃ molding conditions

5. CONCLUSION

In engineering applications, the connection performance of composite materials has a great limit on the application of composite materials. This study discusses the performance of the shear strength of the connection CF/PA6 composites prepared under different connection methods and draws the following conclusions:

- Compares the shear strength of CF/PA6 composite joining prepared by using three types of glue and two instant adhesives to determine the glue suitable for CF/PA6 composite bonding. It was found that polyacrylic acid glue has a better connection effect on CF/PA6 composite materials, and the shear strength of the connection piece using this glue was 53.1MPa.

- The CF/PA6 composite material can be successfully connected by using the conductive properties of CF, and the shear strength increased with the increasing of current and voltage. When the voltage and current value was 10V and 1A, the shear strength of the CF/PA6 composite connector was 62.3 MPa; when the voltage and current value was 10V and 2A, the shear strength of the CF/PA6 composite joining was 81.4 MPa.
- CF/PA6 composite materials are molded and connected by adjusting different hot press molding temperatures and pressures. When the molding temperature was low, the composite material needs greater pressure to produce a better connection; when the molding temperature was higher, the composite material can produce a better connection under a smaller pressure. Among them, the shear strength of the composite material joining was reached the maximum value at temperature of 250 °C and pressure of 2.5 MPa with shear strength of 138.8MPa.

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